Evaluation of SCRs as Millisecond Switches for Electric Gun Launchers

R. Pastore, M. Weiner, H. Singh
US Army Research Lab
Pulse Power Components Branch
Ft Monmouth, NJ

S. Schneider
Consultant
Red Bank, NJ

R. Fox, G. Ayres
Vitronics, Inc.
Eatontown, NJ

Introduction

High power semiconductor switches have the potential of meeting the field system requirements for electric gun launchers. The switch will be required to operate at moderate repetition rates and high coulomb capability with a long lifetime and high reliability. EPSD is presently successfully using spark gaps for switching multi-megajoule capacitor banks for verification of the design of power switching modules for electric gun launchers. Spark gaps are suitable for laboratory experiments because of their fault tolerance and the engineering experience with high current discharges. Solid state switching for electric gun launchers is feasible but not used for existing systems because of the limited knowledge of the behavior of thyristors at high current densities with high rates of rise of current and the need to stack devices for high voltage hold-off. Since semiconductor technology offers the best alternative for meeting lifetime and reliability requirements EPSD has been investigating SCRs for electric gun launcher applications.

Commercial high power SCRs are well characterized and rated for utility applications. An electric gun pulse discharge is sufficiently different in di/dt, pulse length, pulse shape, repetition rate and lifetime that the commercial device ratings no longer apply. SCRs selected for the evaluation had modifications in the gate structure that makes the SCR suitable for use in electric gun systems. SCRs from Power Tech were customized with an involute gate design, the amplifying gate shorted and a stiff gate drive to substantially increase the gate current and thereby improve device turn on performance. An ABB High Current Thyristor (HCT) which has a GTO gate structure was evaluated. This highly interdigitated gate structure gives this device high di/dt capability and the ability to conduct high peak current since the whole device is turned on simultaneously. An optimized GE SCR with a modified snowflake gate structure was investigated. Since the thyristors used in the experiments have modest voltage ratings, they were characterized in 3 low impedance PFNs. In addition a high voltage stack of GE SCRs was evaluated in a 425 kJ module of an electric gun pulser.

Test Conditions

The Power Tech SCR was characterized in a modulator consisting of a 4 section 27 mΩ PFN with a matched load. This network had a total capacitance of 13.6 mF, a voltage rating of 4 kV, a peak current capability of 75 kA, stored charge of 52 C, 104 kJ of energy and a pulse width of 800 µs (FWHM). To achieve higher currents at these low voltages a 15 mΩ/10 mΩ PFN was constructed. The 15 mΩ PFN consists of three each 5 section 45 mΩ PFNs operated in parallel. It has 19 mF of capacitance, a pulse width of 660 µs (FWHM), a peak discharge current capability of 125 kA at 4 kV into a matched load, stored charge of 76 C and a total energy of 152 kJ. The GE SCRs and the ABB HCT were characterized in this setup. By changing the tap positions on the coils the impedance of the network was reduced 10 mΩ. This network has a peak current capability of 200 kA and a pulse width of 490 µs (FWHM). This was done to test the maximum current capability of the ABB HCT. The circuit for the electric gun pulser used in the high voltage tests is shown in figure 1. The characteristics for the three conditions of the circuit are shown in Table I.

Table I Forward Drop Characteristics

	C, µF	L, µH	R_l, mΩ	R_d, mΩ	t_D, ms	t_{rc}, µs	t_{fc}, µs
1	1750	120	400	35	1.063	140	495
2	1750	80	short	30	4	190	2036
3	1750	30	200	20	0.558	77	259

Current measurements were made with a Pearson 2093 current transformer. Forward voltage drops were made with a biased diode circuit. Voltages were measured with Tektronix P6015 1000:1 high voltage probes and P6009 100:1 high voltage probes. All data was collected with a Tektronix DSA 602 digital oscilloscope.

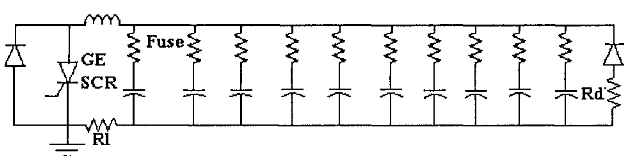

Figure 1. Electric Gun Pulser Circuit. The fuse resistance is 27 mΩ.

Experimental Results

In prior and present experimental studies we determined that the safe operating voltage in pulse applications is 80 % of the nominal breakdown voltage rating. This value held for all types of thyristors and gate designs, including GTO's and MCT's. With rare exception all tests were limited to the safe operating voltage to conserve the limited number of devices available for study. All current rise times mentioned are measured at the 26.6% - 70.1% points. The current fall times are measured at the 70.1%-26.6% points and the fall of anode potential are at the 90%-10% points. All pulse widths are measured at the full width half maximum (FWHM).

Power Tech MT 1313

The Power Tech MT 1313 is a symmetric unirradiated 50 mm SCR with a breakdown voltage of 2500 V. The characterization data for this SCR obtained using the 27 mΩ PFN modulator was

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 1993**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Evaluation of SCRs as Millisecond Switches for Electric Gun Launchers**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **US Army Research Lab Pulse Power Components Branch Ft Monmouth, NJ**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

presented at the 20th Power Modulator Symposium[1]. These devices operating consistently at 2 kV with a peak current of 38 kA. In order to study series/parallel operation, a 2 series by 2 parallel array was constructed for operation at 4 kV and 75 kA. A 400 kΩ resistor divider was added to the array to ensure even voltage division during charging and a saturable reactor was added to the circuit to delay the current pulse until the devices were completely turned on. Isolation transformers were connected to the gates of each SCR to isolate the trigger circuits from the high voltage. The peak current switched by the array was 75.2 kA. The voltage on the upper devices was 4 kV and on the lower devices 2.1 kV. The voltage division of the array was effectively equal. The delay of the saturable reactor was 1.05 μs. The devices switched 56 C. The total energy switched was 113.1 kJ. Figure 2 shows the voltage and current wave forms of the array under these conditions. Figure 3 shows the current sharing of the array at 72.4 kA and 3.86 kV. One stack switched 36.1 kA and the other switched 36.3 kA. The current sharing of the array was within experimental error.

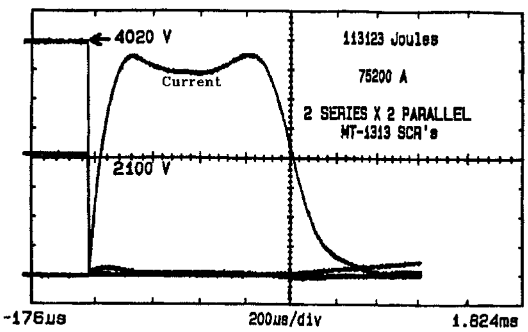

Figure 2. Voltage and current wave forms of 2 series by 2 parallel array at 75.2 kA and 4 kV. 500 V/div and 200 μs/div.

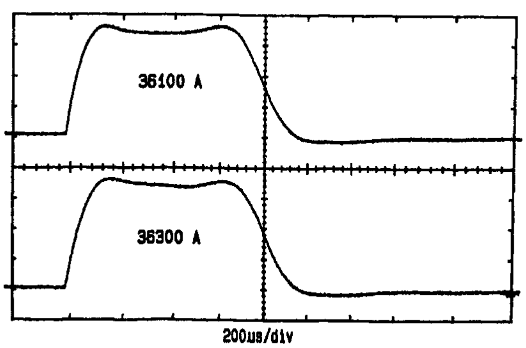

Figure 3. Current wave forms of each stack of MT1313's at 72.4 kA. 10 kA/div.

GE Thyristor

Smaller diameter devices are limited in the amount of current they can conduct so a larger diameter switch was evaluated because it can handle much higher currents. The switch chosen was the GE 6RT305FFW125 100 mm diameter SCR. It has a breakdown voltage of 3.3 kV and surge current rating of 105 kA in a triangular pulse with a base width of over 3 ms. The switch is asymmetric and unirradiated for low forward drop. This SCR has an amplifying gate with a modified snowflake gate structure. GE feels that this gate design is optimum for turn on of the entire active area since it turns the SCR on in 7 different locations. This way there is less conducting area lost than in a device that is highly interdigitated like the GTO. The GTO gate structure means that there are no emitter shorts in the device, so this type of switch is susceptible to dv/dt turn on and has to be biased off to prevent this from occurring.

The GE SCRs were characterized in a 15 mΩ PFN with a matched load. A saturable reactor was used in the circuit in the same manner as it was for the series/parallel array mentioned previously. This circuit is shown in figure 4. Each SCR was characterized up to 2.66 kV at a peak current of 82.6 kA. Each switch was tested 10 times at this level. Current and voltage wave

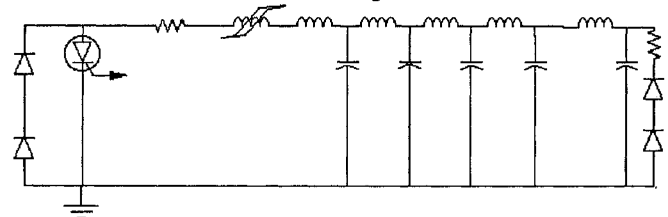

Figure 4. 15 mΩ PFN with 19 mF of capacitance, a total inductance of 4.27 μH, a saturable reactor and inverse clipper.

forms of the SCR are shown in figure 5. The figure displays the current pulse of 82.6 kA with a pulse width of 660 μs, the anode voltage of 2.66 kV. The fall of anode potential is 1.15 μs. The peak current is 82 kA with a rise time of 56.03 μs, a fall of current of 126.6 μs and a di /dt of 627 A/μs. Reliable operation at a high di/dt for this large area device is a result of the gate structure turning on large portions of the device simultaneously. The active area of this device is about 51 cm^2 with a total area of 78.5 cm^2. The current density of the device at this level is 1600 A/cm^2 . The device switched 54.1 C and had an action of 3.7 MA^{2}s. The forward voltage drop data is given in Table II with the corresponding current values.

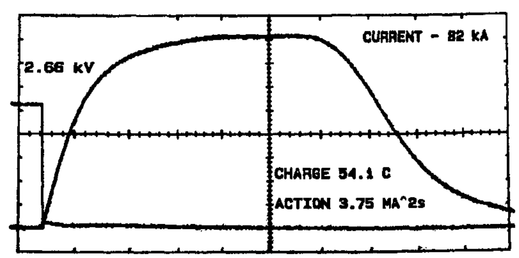

Figure 5. Characterization Current and Voltage of GE SCR. Current Scale is 10 kA/div, Voltage scale 500 V/div. Horizontal scale 100 μs/div.

Table II Forward Drop Data of GE SCR

Time (μs)	50	100	200	300	400	500	550	600
Vdrop (V)	36.8	24.7	14.9	12.5	11.2	10.5	9.4	6.1
Current (kA)	37.6	61.6	76.4	80	81.6	82.6	81.8	75.2

The dissipation in the device was 613.5 kJ, the stored energy of the network was 67.22 kJ giving switching efficiency of 99.08 %.

In order to find the current limit of these SCRs it is necessary to operate them in series so the voltage rating of the devices is not exceeded while operating them at higher peak currents. The first test involved in operating 2 SCRs in series, with a 400 kΩ dividing resistor. Figure 6 are current and voltage wave forms of the switches operating at a total voltage of 3.92 kV. The lower device was at a voltage of 1.96 kV. The voltage division was even in this case. The fall of anode potential for the upper device was 0.679 μs and 0.6 μs for the lower device. The peak current switched was 122 kA with a pulse width of 660 μs. The rise time of the current was 59.18 μs and had a di/dt of 890 A/μs. The total charge switched by the stack was 80 C with a current density of 2.4 kA/cm^2 and an action of 8.2 MA^{2}s. The two devices in the test had two different strain buffers, a solid piece in the upper device and in the lower device a cutout in the shape of the gate. The strain buffer conducts heat out of the gate but in the case of the strain buffer with the cutout there was no path for the heat to be transported out of the gate and it is postulated this caused failure of the of the lower switch. The upper switch in this test was then pulsed 100 times at 2.66 kV and 81.2 kA without any problems.

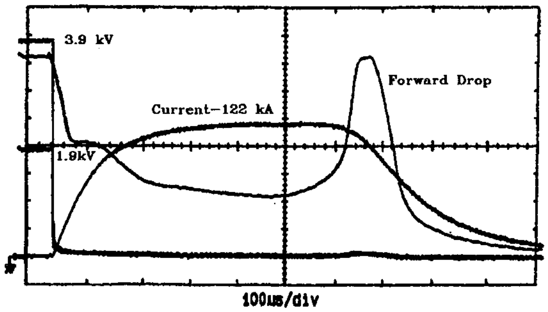

Figure 6. Current and Voltage wave forms for 2 series stack of GE SCRs. Current 25 kA/div. Anode voltage 500 V/div and forward drop 10 V/div.

Ten of these SCRs were operated in series in order to test them in the electric gun modulator. All of these switches had the solid strain buffer. The resistor divider on the stack consist of 10 500 kΩ resistors. The stack was first run in the circuit shown in figure 1 at 22 kV with a 120 μH inductor and a 0.42 Ω in the circuit. The voltage division was approximately equal on the switches. The peak current switched by the stack was 36. kA with pulse width of 1.054 ms. The charge switched was 38.4 C and the action was 1.26 MA^2s. Higher current operation was accomplished by changing the coil to 30 μH and the load to 0.2085 Ω. At 22 kV the stack switched 71 kA at a pulse width of 0.557 ms. The rise time of the current pulse is 81.83 μs and the fall time is 255 μs. The di/dt is 377 A/μs. The charge switched was 40.47 C with an action of 2.07 MA^2s. The wave forms for this operation are in shown figure 7. Tests are under way using the 80 μH coil under short circuited conditions at 22 kV. Under short circuit conditions a snubber was added on each switch consisting of a 47 nF capacitor in series with a 33 Ω resistor to ensure equal inverse voltage division being put on the switches since they have a limited blocking ability in the reverse direction. In the shorted circuit arrangement operating conditions change considerably. The energy is transferred to the inductor which then discharges through the switches and the series diode resistors and results in a longer pulse (4 ms FWHM).

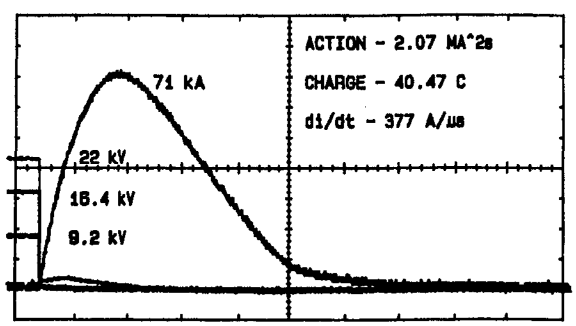

Figure 7. Current and voltage of wave forms of 10 series stack. Current scale 10 kA/div. Voltage 5 kV/div.

ABB High Current Thyristor

The ABB HCT 3001-25A01 is an SCR with a GTO gate structure. This highly interdigitated gate structure greatly improves the di/dt capability of the SCR by turning on the device area uniformly. This technique allows the device to switch large peak currents since it eliminates localized heating caused by the plasma spread. The disadvantage of the switch is it has to be biased off since there are no emitter shorts. In addition, the active emitter area is reduced. The HCT is unirradiated, has a diameter of 80 mm and a breakdown voltage of 2.5 kV. The rated peak current is 150 kA in a 1 ms pulse width. The rated di/dt capability of the HCT is 20 kA/μs. The HCT that was tested at EPSD had a diode mounted in series with it for protection against inverse voltage.

The HCT was characterized up to 2 kV in the 15 mΩ PFN modulator described previously. At 2.0 kV the fall of anode potential was 0.312 μs. The peak current switched was 62.4 kA with a current rise time of 57.78 μs and a di/dt of 460 A/μs. The charge switched was 38.7 C and had an action of 2.16 MA^2s. The forward drop of the HCT was 6 V at 50 μs, increased to 8.8 V at 400 μs and then decreased to 3.6 V at 550 μs. The dissipation in the HCT was 295 J. This rise in the forward drop is caused by the current heating the device. ABB stated as the current approaches the peak current limit of the switch the forward drop curve will become more parabolic and eventually becoming triangular. This is the sign of non-uniform current distribution and approaching failure. The PFN impedance was reduced to 10 mΩ to study it at higher currents. The peak current at 2 kV was 92 kA with a current rise time of 66.07 μs and a di/dt of 598 A/μs and a pulse width of 490 μs. The action was 3.15 MA^2s. The forward drop of this device is listed in Table III.

Table III. Forward drop data for HCT

Time (ms)	50	100	200	300	400	500	550	600
Vdrop (V)	6.8	9.19	9.6	12	11.6	9.6	7.6	6.8
Current (kA)	38	64	84	91	87	70	44	30

Figure 8 shows the current and voltage wave forms under these conditions. The forward drop is higher at this current level. The dissipation in the device is 447 J.

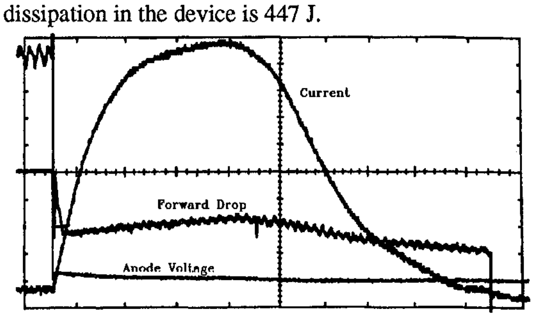

Figure 8. Characterization current and voltage wave forms of ABB HCT. Current scale 10 kA/div, peak current is 92 kA. Anode voltage scale 500 V/div, voltage is 2 kV. Forward drop 10 V/div.

Since the limiting factor in testing at higher currents is the 2 kV voltage rating, it was placed in series with a GE thyristor to try and test to 150 kA or the point where the forward drop of the HCT shows the device heating non uniformly. The series stack was operated up to 2.54 kV with a peak current of 114 kA. The current rise time of 69.14 μs with a di/dt of 698.3 A/μs. Figure 9 shows the HCT and GE SCR in operation at 2.54 kV. The forward drop wave form is the forward drop of the HCT plus the diode in series with it for protection. Signs of heating are evident in this wave form. As the HCT starts to conduct the drop increases to 110 V, decreases to 45.6 V at 300 μs, increased to 86.4 V at 356 μs and then fell rapidly. This high voltage drop is evidence of heating of the HCT. To make the forward drop measurement of the HCT alone it is necessary to repeat the test measuring the forward drop of the series diode so this can be subtracted from the total drop measurement to obtain the HCT forward drop. During the recharge to 2.54 kV the switches self triggered indicating that they were damaged during the previous shot. Both switches were shorted but the gates still worked indicating the failure was in the active areas of both devices. The action of the switches was 4.85 MA^2s and the HCT plus the series diode had a dissipation of 2.28 kJ.

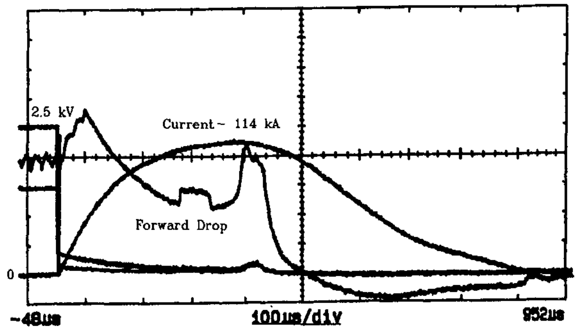

Figure 9. Current and Voltage wave forms of ABB HCT in series with GE SCR. Current 25 kA/div, Voltage 500 V/div, forward voltage 10 V/div.

Conclusion

Several low impedance modulators have been built to test individual solid state switches with various gate designs. The thyristors have been obtained from GE, ABB, and Power Tech. the gate designs include modified snowflakes, involute, and GTO designs. Current densities of 2.4 kA/cm^2, have been demonstrated at 125 kA and rate of rise of current of 890 A/µs with switching efficiencies in excess of 99%. Series and parallel switch arrays have been demonstrated. A series switch array of GE thyristors has been built with an operational rating of 26 kV and 100 kA. It has been operated at 22 kV and 71 kA and reliably switched a 425 kJ capacitor bank.

Acknowledgments

We would like to thank Mr. Rolf Dethlefsen of Maxwell Laboratories for his suggestions and providing us with the ABB HCT. We would like to thank Mr. Bill Tobin of General Electric SPCO for making the SCRs and providing us with valuable information on their behavior.

References

[1] R. Pastore, C. Braun, S. Schneider, J. Carter, R. Fox, "Preliminary Evaluation of High Power Solid State Switches for Electric Guns Applications," in Proceedings of the 20th Power Modulator Symposium, 1992, pp. 281-284.